Risk Mitigation for High Temperature Superconducting Generators

R.L. Holtz
Materials Science and Technology Division

Background: High temperature superconducting (HTS) motors and generators will enable high-efficiency, high power density naval propulsion, and compact electrical generators for weapons and ship systems. The second-generation high temperature superconductors (2G-HTS) based on yttrium-barium-copper-oxide (YBCO) coated conductor architectures have undergone a processing technology breakthrough that has led to manufacturability of long lengths of these materials, sufficient for demonstrations of large motors and generators. Ensuring superior fatigue properties of the HTS materials compatible with the life-cycle of naval machinery is a key issue. NRL has been working closely with superconductor manufacturer Superpower, Inc., electric motor manufacturer Baldor Reliance, General Dynamics Electric Boat Division, and Naval Surface Warfare Center Carderock Division (Philiadelphia) on risk mitigation demonstrations for a 10 MW HTS generator design. NRL's responsibility in this collaboration is assessment of the reliability of HTS coil design, particularly with respect to thermomechanical fatigue associated with cooling/warming between room temperature and the cryogenic temperatures at which the machines operate.

Coil Architecture for HTS Machinery: Figure 4 depicts a rotor coil architecture for an HTS motor or generator. The windings of HTS tapes are placed into a steel or other metallic rotor structure, and secured by epoxy impregnation. The epoxy provides both mechanical support against the high stresses experienced by the coil, and electrical insulation. The principal risk factor for the reliability of such coils is thermomechanical stress as the coil is cooled to cryogenic temperatures. If a coil is subsequently warmed and cooled multiple times, such as for major maintenance, overhaul, or repair of the machine, there is a potential for low cycle fatigue damage. In the life of a ship generator, such thermal cycles would occur perhaps up to 20 to 30 times.

The large thermomechanical stresses develop because between room temperature and 77 K, the thermal contractions of epoxies with suitable strength and electrical properties are typically around 1%, while the thermal contractions of the HTS tapes and of the steel are much lower, around 0.25%. Thus, large tensile stress develops in the epoxy, which potentially could rupture the HTS tapes, damage electrical connections, or crack the interface between the epoxy and the HTS or the interface between the epoxy and the steel rotor body.

Coil Electrical Characteristics: The main measurements we perform on HTS coils are the voltage versus current curves, and the time dependence of voltage for fixed currents. Typical behaviors at 77 K are shown in Fig. 5. The voltage-current curves are characterized by a voltage that grows exponentially as current increases above a "critical current." In an ideal HTS tape, the DC resistance is zero for currents below the critical current. In a real coil, there are splices of HTS tapes, as well as joints of HTS tapes with copper conductors. These have a small DC resistance, which manifests as a linear behavior at low currents in the voltage-current curves, indicated in Fig. 5(a). For thermomechanical fatigue reliability evaluation, any increases in the resistance following thermal cycling would indicate damaged electrical connections or splices.

When the current exceeds the critical current anywhere in the coil, heat is produced, which raises the temperature, which reduces the critical current even further, leading to a thermal runaway process known as "quench." This manifests as a voltage that increases with time at constant current, as seen for the higher currents in Fig. 5(b). An important figure of merit therefore is the maximum current that can be used in the coil without causing thermal runaway. We term this the "quench instability current." For thermomechanical fatigue reliability assessment, we measure this quench instability current as a function of thermal cycles. Changes in this property would indicate either damage to the HTS tapes, or cracks separating the epoxy from the HTS or the steel body, which degrade the thermal conductivity.

Results: Figure 6 shows results from NRL's recent evaluation of a prototype HTS generator coil. No systematic changes of the resistive component, Fig. 6(a), or quench current, Fig. 6(b), are seen for up to 20 thermal cycles between room temperature and cryogenic temperatures.

Significance: Prior work at NRL on the electromechanical properties of HTS tapes established limits on the stresses and strains that could be tolerated.[1] By incorporating earlier NRL results into the design of coils, risk of degradation due to thermal cycling is mitigated. Actual measurements on prototype coils under the current NRL program confirm the fatigue integrity of coil designs, and demonstrate that HTS technology is reliable for large, fatigue-critical, shipboard machinery applications.

Acknowledgments: HTS coils were provided by Superpower, Inc., Schenectady, NY.

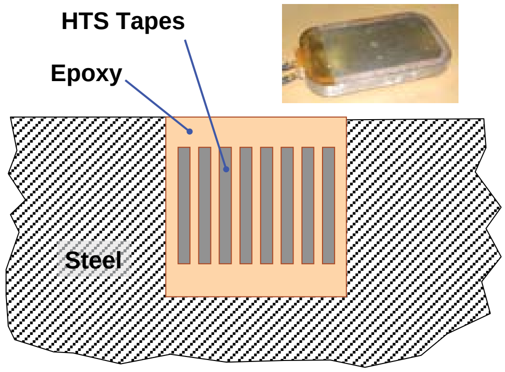

FIGURE 4
Schematic of the cross-sectional coil architecture. HTS windings are placed into steel body and epoxy-impregnated. The inset shows an example of a prototype coil.

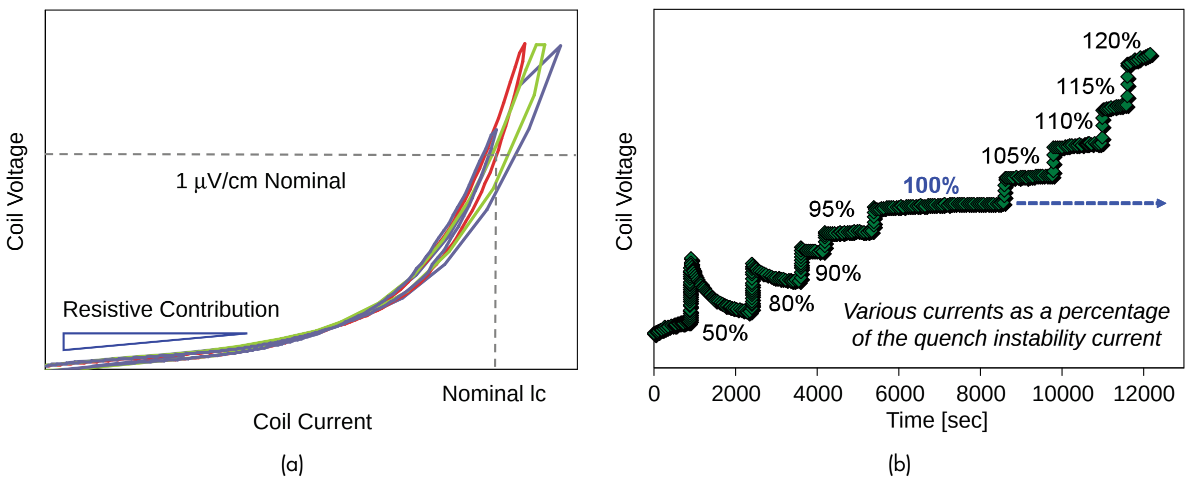

FIGURE 5
(a) Typical voltage-current curves for an HTS coil. This plot shows the curves following several different thermal cycles. The nomimal criticial current, Ic, is defined as the current at which the voltage is 1 microvolt per centimeter. The linear behavior at low currents is due to a resistive (non-superconducting) contribution. (b) Typical voltage-time curves for the same HTS coil. For each value of current, the voltage is monitored for some period of time to determine if it is stable. The highest current at which the voltage exhibits long term stability is designated the quench instability current.

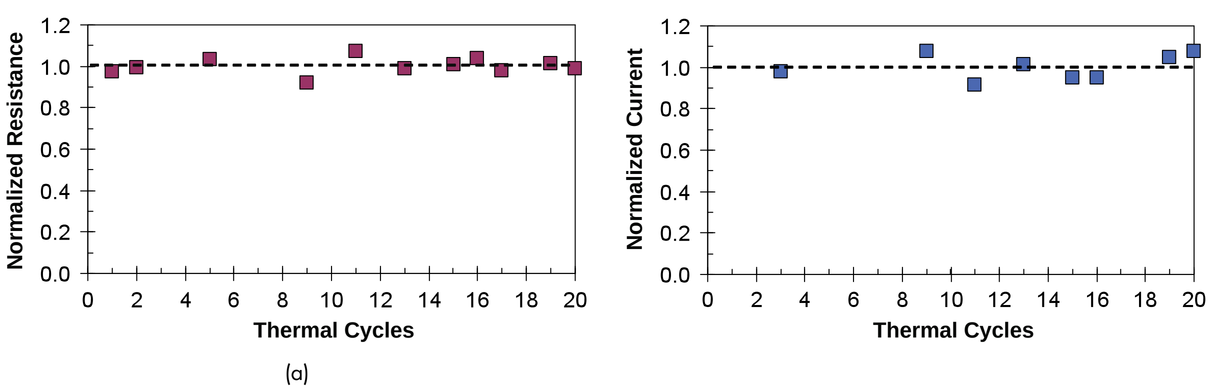

FIGURE 6
Experimental results on an HTS coil showing the thermal cycling stability of the (a) resistive contribution to the voltage-current characteristics, and (b) the quench instability current. Results are normalized to the average values in both plots.

[Sponsored by ONR and NRL]

Reference

[1] R.L. Holtz, R.J. Soulen, M. Osofsky, J.H. Claassen, G. Spanos, D.U. Gubser, R. Goswami, and M. Patten, "High Temperature Superconductors for Naval Power Applications," *2006 NRL Review*, pp. 149–151.